Liquid crystals: a new topic in physics for undergraduates

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Abstract. The paper presents a teaching module about liquid crystals. Since liquid crystals are linked to everyday student experiences and are also a topic of a current scientific research, they are an excellent candidate of a modern topic to be introduced into education. We show that liquid crystals can provide a *file rouge* through several fields of physics such as thermodynamics, optics and electromagnetism. We discuss what students should learn about liquid crystals and what physical concepts they should know before considering them. In the presentation of the teaching module that consists of a lecture and experimental work in a chemistry and physics lab, we focus on experiments on phase transitions, polarization of light, double refraction and colours. A pilot evaluation of the module was performed among pre-service primary school teachers who have no special preference for natural sciences. The evaluation shows that the module is very efficient in transferring knowledge. A prior study showed that the informally obtained pre-knowledge on liquid crystals of the first year students on several different study fields is negligible. Since the social science students are the ones that are the least interested in natural sciences it can be expected that students in any study programme will on average achieve at least as good conceptual understanding of phenomena related to liquid crystals as the group involved in the pilot study.

1. Introduction

For physicists physics is a permanent inspiration for new discoveries. However, non-physicists often consider physics as a boring and old discipline, detached from everyday life. Public often fails to realize the consequences of research in everyday applications, so it often considers the academic research as a waste of financial resources. But research is tightly connected to the development even if it is not strongly focused toward applications. This can be best illustrated by the well known statement that "the light bulb was not discovered by optimizing a candle"[1, 2]. The apparent non-relevance of physics for the everyday life is often caused by the choice of topics taught during the lectures, which are usually old from the point of young students, since even the most recent topics - fundamentals of modern physics - are more than a hundred years old [3]. In addition, traditional teaching very often considers idealized examples and, worst of all, present experiments as a "proof"for theoretical explanations.

The physics education research has pointed out several of these problems and the physics education in general has advanced tremendously in the last twenty years [4]. But topics that introduce a part of the frontier research into the classroom, showing the students that the physics is not a dead subject yet, are still extremely rare.

In this paper we present a topic, liquid crystals, which is one of rare examples, where such a transfer is possible. The community occupied by the research on liquid crystals counts several thousands of researchers. We all experience the consequences of research on liquid crystals every day; every mobile phone, every portable computer and almost every television screen is based on the technology using liquid crystals.

The physics of liquid crystals is not very simple but there are several concepts that can be understood by non-physics students as well, especially if the teaching approach is based on gaining practical experiences with liquid crystals. In addition, for advanced levels of physics students, liquid crystals may serve as a clear illustration of several concepts especially in thermodynamics and optics.

A serious interest of researchers for an introduction of liquid crystals into various levels of education was first demonstrated at The International Liquid Crystal Conference (ILCC) in Krakow, Poland, in 2010. ILCC is a biennial event gathering more than 800 researchers studying liquid crystals from a variety of aspects. In Krakow, one of four sections running in parallel was called *Liquid Crystals in Education*. The audience unexpectedly filled the auditory to the last corner and after lectures lengthy discussions developed [5]. A similar story repeated at the education section at the European Conference on Liquid Crystals in Maribor, Slovenia, in 2011, and at ILCC in Mainz, Germany, in 2012.

At present, some of the physics of liquid crystals is usually briefly mentioned at various courses at the university level, but there is no systematic consideration from the education perspective about the importance of various concepts and teaching methods. To our best knowledge, there exist no example of a model teaching unit. In this contribution we report on a teaching module on liquid crystals, which is appropriate

for the undergraduate level for non-physicists. The module can be extended to the lab work at more advanced levels. Most of the module can also be used in courses related to thermodynamics and optics as demonstration experiments or lab work accompanied by more rigorous measurements and calculations, which are not considered in detail in this contribution.

The paper is organized as follows: in section 2 we consider the prerequisites for the introduction of new modern topic into education. Before designing a module we had to consider several points, not necessary in the same order as quoted here: What outcomes do we expect of the teaching module? Which are the concepts that students should understand and be able to apply after the module? Where in the curriculum should the topic be placed, or equivalently, what is the knowledge students need to be able to construct new knowledge about liquid crystals? Which teaching methods are most appropriate for the teaching module? And finally, do we have all the materials like experiments, pictures, equipment and facilities to support the teaching module? In section 3 we report the pilot evaluation study of the teaching module, which was performed in 2011. In section 4 we conclude and discuss several opportunities that the new teaching module offers to the physics education research in addition to the new knowledge itself.

2. Teaching module

When we consider a new topic which is a part of contemporary research with applications met every day, and we want to adapt it for teaching purposes, the literature search is not much of a help. A thorough literature search did not show any theoretical frameworks on this topic. One can find theoretical frameworks for various approaches to teaching and discussions about students motivation and understanding of various concepts. We have found few examples of introduction of new topics like an introduction of semiconductors into the secondary school or introduction of more advanced concepts with respect to friction only [6, 7]. There are also examples of introduction of concepts of quantum mechanics into high school [8, 9, 10, 11]. All authors reported similar problems with respect to the existing theories and results in physics and science education research; they had to build the units mostly from the personal knowledge, experience and considerations. On the other hand, several approaches for analytical derivation of already treated concepts, several suggestions for demonstrations and lab experiments for teaching purposes are published in every issue of the American and European Journal of Physics. This simply means that the physics community is highly interested in the improvement of the teaching itself, but the motivation of the researchers, being also lecturers, lies more in the area of developing new experiments than in thorough studies of their impact. Therefore, a lot of material for teaching purposes for any topic, old, modern or new is available, but one further step is usually needed towards the coherent teaching module.

With the above mentioned problems in mind, we begin by brief discussion on what

liquid crystals are and then give a short overview of the existing literature regarding the introduction of liquid crystals into teaching. Then we focus on the teaching module: we define our goals, consider the pre-knowledge on which the module should be built and finally describe details of the module.

2.1. What are liquid crystals?

Liquid crystals are materials which have at least one additional phase between the liquid and the solid phase. This phase is called the liquid crystalline phase and it has properties of both the liquid and the crystalline phase: a) it flows like a liquid, or more fundamental, there is no long range order in at least one of directions, and b) it is anisotropic, which is a property of crystals, or, again, more fundamental, there exists a long range order in at least one of directions. The name liquid crystal is the name for the material, which exhibits at least one liquid crystalline phase [12].

Liquid crystalline phases differ by the way of long range ordering. In this contribution we will discuss only the simplest type of ordering that is typical for the nematic phase. Its properties are applied in a liquid crystalline screen. The molecular order in the crystalline phase is shown schematically in figure 1 (a), in the nematic liquid crystalline phase in figure 1 (b) and in the isotropic liquid phase in figure 1 (c). One can see that, in the liquid crystalline phase, there exists some orientational order of long molecular axes. Such a material is anisotropic, the physical properties along the average long molecular axis obviously being different from the properties in the direction perpendicular to it. There are several liquid crystal phases made of molecules having rather extravagant shapes. However, we shall limit our discussion to the simplest case of nematic liquid crystal made of rod-like molecules without any loss of generality of the phenomena studied within the teaching module.

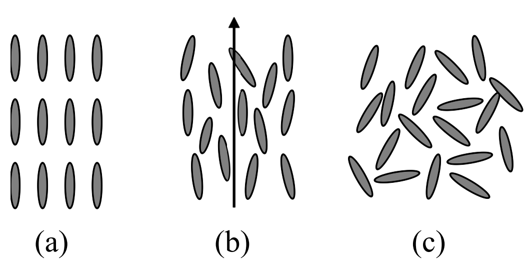


Figure 1. Molecules of liquid crystal in different phases; (a) crystalline, (b) liquid crystalline (nematic) and (c) isotropic liquid.

When liquid crystal molecules are close to surfaces, surfaces in general tend to prefer some orientation of long molecular axes. Using a special surface treatment one can achieve a well-defined orientation of long molecular axes at the surface, for example, in the direction parallel to the surface or perpendicular to it. In liquid crystal cells, which are used in liquid crystal displays (LCDs), surfaces are usually such that they anchor the molecules by their long molecular axes in the direction parallel to the surface; however

orientations of molecules at the top and bottom surface are perpendicular. Molecules between the surfaces tend to arrange with their long axis being parallel, however due to the surface anchoring their orientation rotates through the cell (figure 2 (a)). Because in the anisotropic materials the speed of light depends on the direction of light propagation and on the direction of light polarization, liquid crystals organized in such a special way rotate direction of light polarization. If such a cell is put between two crossed polarizers whose transmission directions coincide with the direction of surface anchoring, the cell transmits light [12, 13].

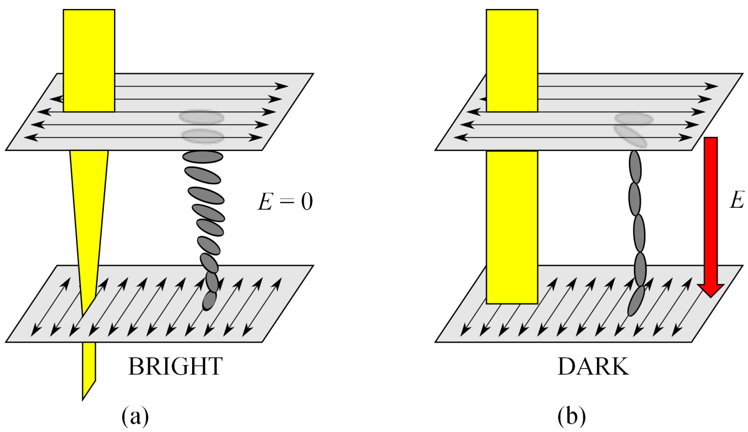


Figure 2. The arrangement of molecules in cells used for displays. (a) The "bright state": without an applied electric field ($E = 0$) the cell transmits light; (b) the "dark state": when voltage is applied to the two glass plates molecules rearrange and the cell does not transmit light.

Liquid crystals are also extremely useful in discussing different competing effects that determine the molecular arrangement. Application of an external magnetic or electric field changes the structure in the liquid crystal cell described above, because the electric or magnetic torque tends to arrange molecules in the direction parallel or perpendicular to the external field, depending on the molecular properties. Rotation of molecules in the external field changes the optical transmission properties of the cell. This is a basis of how LCDs work: with the field on (figure 2 (b)), light is not transmitted through a cell and the cell is seen to be dark; with the field off (figure 2 (a)), light is transmitted through the cell and the cell is seen to be bright.

Because of their unique physical properties several authors have already considered the introduction of liquid crystals into the undergraduate university studies. A mechanical model of a three dimensional presentation of liquid crystals phases is presented in [14]. The historical development of the liquid crystals research and their application is given in [15]. In [16] the same authors point out that liquid crystals are an excellent material to connect some elementary physics with technology and other scientific disciplines.

The procedures to synthesize cholesteric liquid crystals (nematic liquid crystals in which the average orientation of long molecular axes spirals in space) in a school lab

at the undergraduate university level are given in [17, 18] together with the methods to test the elementary physical properties of liquid crystals. In the Appendix to [18] an experiment to determine refractive indices of a liquid crystal is discussed [19]. The anisotropic absorption of polarized light in liquid crystals is presented.

Liquid crystals that are appropriate for the education purposes are thermotropic; their properties change with temperature. The colour of cholesteric liquid crystals changes if temperature increases or decreases, so they can be used as thermometers [20]. They are also sensitive to pressure. Reference [21] contains worksheets for an experiment in which students discover the sensitivity of cholesteric liquid crystals mixtures on pressure and temperature. In [22] a simple experimental setup is presented by which students can detect and record the light spectra, study and test the concept of Bragg reflection, and measure the anisotropy of a refractive index in a cholesteric liquid crystal.

A series of simple experiments that can be shown during lectures and can bring the science of liquid crystals closer to students is described in [23]. The experiments are used to introduce the concepts of optics, such as light propagation, polarization of light, scattering of light and optical anisotropy. Liquid crystal can also be used to describe light transmission through polarizers [24]. When an external field is applied to a cell, a threshold value is required to rotate molecules in the direction preferred by the field. This effect is called the Freedericksz transition and an experiment for the advanced physics lab at the undergraduate level is presented in [25].

The procedure to prepare a surface-oriented liquid crystal cell is given [26] where the procedure to synthesize a nematic liquid crystal 4-methoxybenzylidene-4'-n-butylaniline (MBBA) is provided as well. Several experiments that illustrate optical properties of liquid crystals are shown. One learns how to design a cell in which molecules are uniformly oriented and what is observed, if this cell is studied under the polarizing microscope. A detailed description of phase transitions between the liquid, liquid crystal and crystal phases is given. Exercises are interesting for undergraduate students because they synthesize the substance which they use for other experiments, e.g. measurements of the refractive indices.

There are several advanced articles which give advice on the inclusion of liquid crystals into the study process at the university, both undergraduate or graduate, level. An experiment for the advanced undergraduate laboratory on magnetic birefringence in liquid crystals is presented in [27], measurements of order and biaxiality are addressed in [28]. In [29] defects in nematic liquid crystals are studied by using Physics Applets [30]. Liquid crystals are not used only in displays but also in switches. In [31] a liquid crystal spatial light modulator is built and used for a dynamic manipulation of a laser beam.

2.2. What should students learn about liquid crystals?

When discussing an introduction of a new topic into education, the team should be aware of the goals as well as of limitations. There are no general criteria established

about the concepts that student should learn and comprehend, when a new topic is introduced. Therefore, for liquid crystals, we had to rely on our understanding of the topic; we had to neglect our personal bias toward the matter as two of the authors are also active researchers in the theoretical modeling of liquid crystals. Being an expert in the research of liquid crystals may also over or under estimate the concepts that are important for students. We hope that we managed to avoid these "personal" traps.

The aim of the teaching module is to explain how LCDs work and what is the role of liquid crystals in its operation. We also believe that some basic understanding of LCDs is a part of a general public knowledge, because it is an important example of the link between the academic research and the applications, which follow from it. If non-physics students meet such an example at least once during their studies, they might not consider the academic research that has no immediate specific application as obsolete.

According to our opinion students should obtain and understand the following specific concepts:

- they should be able to recognize and identify the object of interest - the pixel - on an enlarged screen;
- they should be aware of the fact that liquid crystals are a special phase of matter having very special properties;
- they should become familiar with the following concepts: anisotropy, double refraction and birefringence;
- they should be aware of the fact that liquid crystals must be ordered if we want to exploit their special properties;
- they should know that liquid crystals are easily manipulated by external stimuli like an electric field; and finally
- they should link the concepts mentioned above in a consistent picture of pixel operation.

Before constructing the teaching module we have thus set the goals stated above. The next steps are: a) to consider the required knowledge before the students start the module, b) to position the topic in the curriculum, otherwise teachers will probably not adopt it and c) to choose the methods, which will be the most successful for constructing the new knowledge.

2.3. Which basic physics concepts should students know before considering liquid crystals?

As liquid crystals are materials which form a special liquid crystalline phase, students should be familiar with a concept of phases. They should be aware of a phase transition that appears at an exact temperature. Students very often believe that mixture of ice and water can have any temperature as they often drink mixtures of ice and water, which are not in a thermodynamically stable state yet.

The next important concept is the speed of light in a transparent medium, its relation to the index of refraction and Snell's law. If students are familiar with the concept of polarized light and methods of polarizing the light, it is an advantage. However, polarization of light can also be nicely taught when teaching the properties of liquid crystals.

Students should also know, at least conceptually, that materials electrically polarize in an external electric field and that the material polarization (not to be confused with polarization of light!) is a consequence of structural changes of a material in the electric field.

Considerations of the required preliminary students knowledge also give some hints about the placement of the topic on liquid crystals in the curriculum:

- When teaching thermodynamics or, more specifically, phases and phase transitions, additional phase can be visually shown by liquid crystals, since the appearance of liquid crystals in their liquid crystalline phase is significantly different from their solid or liquid state. This is not the case for other materials, for example, a ferromagnetic material or a superconductor looks exactly the same when the phase transition to the ferromagnetic or superconductive phase appears at the transition temperature. The phase transition has to be deduced from other properties.
- When Snell's law is introduced and prisms are discussed, a rainbow is often added as an interesting phenomenon that is observed because the speed of light depends on its wavelength. Similar phenomenon, i.e. a dependence of the speed of light on light polarization can be discussed by a phenomenon of a double refraction.
- One picture element (pixel) is formed by confining LC between two conducting plates. One pixel is thus a capacitor with a dielectric material (liquid crystal) between the plates. When voltage is applied to the cell surfaces (capacitor plates), the material between the plates polarizes. Electric polarization leads to changes in structural properties of the materials, in this case to the reorientation of molecules, which affects the transmission of light through the cell. Thus a LC pixel can be used to consider electric polarization of other materials that can structurally change due to the reorientation of molecules.

From the above we clearly see that liquid crystals can provide a motivational *file rouge* through several topics. On the other hand, by showing several phenomena related to liquid crystals, teachers can motivate students to remain interested in various topics in physics and link them together in the explanation of how one pixel in a liquid crystal display works. Teachers can choose to teach about liquid crystals as a separate topic aiming to establish a link between a current fundamental research topic and consequences of the research applied and used every day by everybody.

The last question that remains to be answered is a choice of methods for the teaching intervention. Liquid crystals are a new topic for students. They are mostly only slightly familiar with the name and have practically no associations connected to the name except a loose connection to displays, as will be shown later. Therefore the topic

should be introduced from the very beginning. Due to several concepts that must be introduced and the structure of understanding that students have to build without any pre-knowledge, traditional lecturing seems the most natural choice. However, from the literature and our experiences we are aware that the transfer of knowledge to relatively passive students is not as successful as one would wish for. Therefore we decided to use a combination of a traditional lecture accompanied by several demonstration experiments, where most of the fundamental concepts and properties are introduced, a chemistry lab, where students synthesize a liquid crystal, and a physics lab, where they use their own product from the chemistry lab to study its various physical properties by using an active learning approach. The lab work allows students to construct and to comprehend several new ideas that are all linked together in the application, a liquid crystalline display.

2.4. The teaching module

The teaching module gives the basic knowledge about liquid crystals, which we assessed as necessary for the understanding of liquid crystals and liquid crystal display technology for a general citizen having at least a slight interest in science and technology. The teaching module has three parts: lecture (1st week), lab work at chemistry (2nd week) and lab work at physics (3rd week). The estimated time for each part is 90 minutes. Within the teaching module we wanted the students to assimilate the following concepts: a) a synthesis of a liquid crystals MBBA [32, 33], b) an existence of an additional phase and phase transitions, c) polarization of light and d) optical properties of liquid crystals related to anisotropy [33]. Below we present the module, its aims, its structure and a short description of activities in each part of the teaching module.

2.4.1. Lecture The lecture in duration of 90 minutes provides the fundamental information about liquid crystals, about their properties and how they are used in applications. The method used is a traditional lecture accompanied by several demonstration experiments that are used for motivation, as a starting point for discussion and as an illustration of phenomena discussed.

After the lecture students should be able to

- list some products based on the liquid crystal technology;
- recognize the additional liquid crystalline phase and phase transition;
- describe and illustrate the structure of liquid crystals on a microscopic level;
- recognize the properties of liquid crystals, which are important for applications: birefringence, resulting from the orientational ordering of molecules, and the effect of an electric field on molecular orientation;
- describe how a LCDs work;
- know that liquid crystals are also found in nature and that they are present in living organisms.

In addition, a short part of the lecture introduces polarizers and their properties, since most of the students have not heard of the concept of polarization and polarizers during their previous education.

The lecture starts with a magnification of a LC screen as a motivation; it is explained that at the end of the module students will be able to understand how the display works. The lecture continues with a description and a demonstration of the new, liquid crystalline, phase, the macroscopic appearance of which is similar to an opaque liquid. All three phases (crystalline, liquid crystalline and isotropic liquid) are shown while heating the sample. The microscopic structures of all three phases are presented by cartoons and the orientational order is introduced. The molecular shape which allows for the orientational ordering is discussed. The concept of light propagation in an anisotropic material is introduced and double refraction is shown by using a wedge liquid crystalline cell. Colours of an anisotropic material (scotch tape) between crossed polarizers are demonstrated and explained. When polarized light propagates through an anisotropic material, the polarization state of light, in general, changes from the linearly polarized to elliptically polarized. The state of elliptical polarization is defined by the wavelength of light, the birefringence of the anisotropic material (i.e. the difference between the refractive indices) and the thickness of the material. The understanding of how polarized light propagates through a birefringent (optically anisotropic) material is crucial for understanding the pixel operation.

In the LCDs the electric properties of molecules are very important so they have to be introduced in the lecture. The effect of the electric field on the molecular orientation is discussed as well. Molecules are described as induced electric dipoles that are rotated by the external electric field. Because the anisotropic properties depend on the structure of the liquid crystal in the cell, the transmission depends on the applied electric field. This leads to the structure of a pixel and to how liquid crystal displays work.

At the end of the lecture some interesting facts are mentioned, such as liquid crystals being a part of spider threads and cell membranes in living organisms.

2.4.2. Lab work in chemistry: synthesis of liquid crystal MBBA The aims of the lab work in chemistry are the following:

- Students are able to synthesize the liquid crystal MBBA.
- Students realize that the product of the synthesis is useful for the experiments showing the basic properties of liquid crystals.

Students synthesize the liquid crystal MBBA in a school lab from 4'-n-butylaniline and of 4-methoxybenzaldehyde [33]. Due to the safety reasons, the synthesis has to be carried out in the fume hood. This part of the teaching module can be left out if the laboratory is not available and the lab work in physics could extend to two meetings of the duration of 90 minutes, which allows for more detailed studies of phenomena.

2.4.3. Lab work in physics Four experiments that are carried out during the lab work in physics provide students with personal experiences and allow them to investigate the most important liquid crystalline properties.

Experiment 1: An additional phase and phase transition
Aims:

- Students know that the liquid crystalline state is one of the states of mater.
- Students are able to describe the difference between the melting temperature and the clearing temperature.
- Students are able to measure these two temperatures and use them as a measure of the success of the synthesis. If both temperatures are close to the temperatures given in the published data, the synthesis was successful.

Students use a water bath to heat the test tube with a frozen liquid crystal MBBA. They measure the temperature of water assuming that the small sample of liquid crystal has the same temperature as the bath. They observe how the appearance of the substance changes (figure 3) while heating the water bath. They measure the temperature at which the sample begins to melt. This temperature is called the melting temperature and it is the temperature of the phase transition from the crystalline to the liquid crystalline phase. Students heat the water bath further and measure the temperature at which the milky appearance of the sample starts to disappear. This temperature is called the clearing temperature and it is the temperature of the phase transition from the liquid crystalline phase to the isotropic liquid.

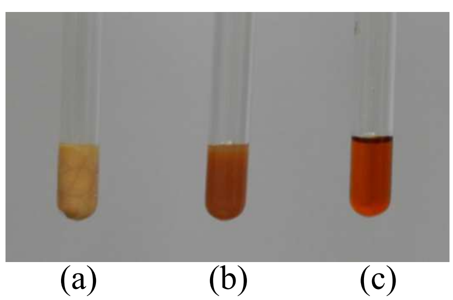


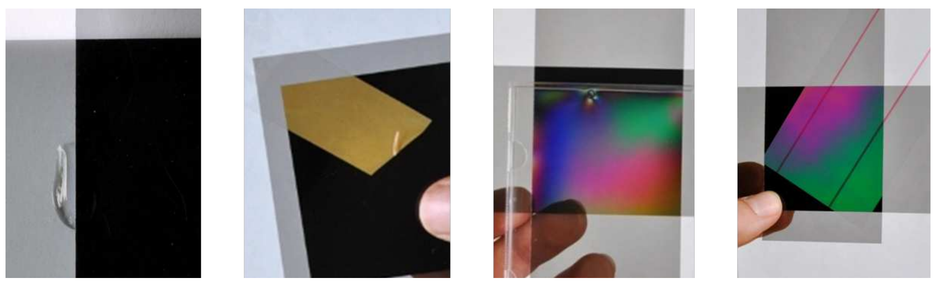
Figure 3. The phases of the liquid crystal MBBA: (a) solid, (b) opaque liquid crystalline and (c) clear isotropic liquid.

Experiment 2: Polarization
Aims:

- Students know what polarizers are and how they affect the unpolarized light.
- Students know how light propagates through the system of two polarizers.
- Students are able to test, if the light is polarized and in which direction it is polarized by using the polarizer with a known polarizing direction.
- Students are able to test if the substance is optically anisotropic by using two polarizers.

Students use two polarizers and investigate the conditions under which light propagates through two polarizers or is absorbed by them. They compare the transmitted light intensity as a function of the angle between the polarizing directions of polarizers. By this part of the activity they learn how to use a polarizer as an analyzer. They also verify that the reflected light is partially polarized.

Students observe various transparent materials placed between crossed polarizers and find that light cannot be transmitted when (isotropic) materials like water or glass are placed between the crossed polarizers. When some other material like a scotch tape, cellophane or CD box is placed between the crossed polarizers, light is transmitted. Colours are also often observed (figure 4). Such materials are anisotropic. Students can investigate how various properties of anisotropic materials (thickness, type of material) influence the colour of the transmitted light. The activity provides an experience that is later used for observations of liquid crystals in a cell.



(a) (b) (c) (d)

Figure 4. Various materials between crossed polarizers: (a) an isotropic drop of water, (b) a piece of a scotch tape, (c) a transparent CD box and (d) a cellophane.

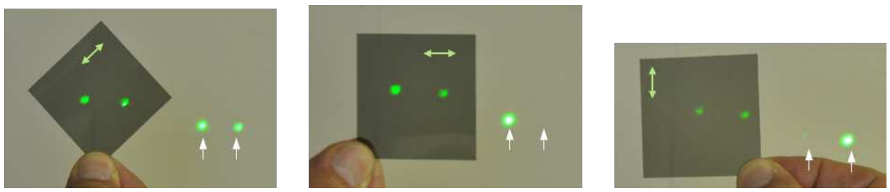
Experiment 3: Double refraction

Aims:

- Students know that birefringence is an important property of matter in the liquid crystalline state.
- Students are able to make a planar wedge cell and find an area where liquid crystal is ordered enough that the laser beam splits into two separate beams. The beams are observed as two light spots on a remote screen.
- Students know how to check light polarization in a beam by a polarizer.

Students manufacture a wedge cell from a microscope slide, a cover glass, a foil for food wrapping or a tape and the liquid crystal MBBA [33]. A special attention is given to the rubbing of the microscope and cover glass, which enables anchoring of the liquid crystal molecules. The rubbing also prevents the disorder of clusters of molecules with the same orientation of long molecular axis; such clustering results in scattering of light and opaqueness. Students direct the light on the wedge cell (they use a laser pointer as the light source) and find the area of the cell where the laser beam splits into two beams. By rotating the polarizer between the cell and the screen they verify light polarization in

the beams (figure 5). Then students heat the wedge cell with the hair-dryer and observe the collapse of the two bright spots into one at the phase transition to the isotropic liquid.



(a) (b) (c)

Figure 5. Finding the polarization direction of beams transmitted through the LC wedge cell. The arrow on the polarizer marks the polarizing direction of the polarizer. The polarizer transmits (a) both beams, (b) only the extraordinary beam, (c) only the ordinary beam. Polarization of the ordinary beam is perpendicular to the polarization of the extraordinary beam. Two small arrows marking the light spots are used as a guide to the eye.

Experiment 4: Colours

Aims:

- Students are able to fabricate a planar cell, i.e. a cell with parallel glass surfaces.
- Students know that liquid crystals are optically anisotropic and that light is transmitted if a cell filled with liquid crystal in its liquid crystalline phase is placed between two crossed polarizers.They know that under such circumstances colours may also appear when the sample is illuminated by white light.
- Students know that the colours observed under perpendicular and under parallel polarizers are complementary.
- Students are able to mechanically order molecules in a planar cell.

Students manufacture a planar cell filled with the liquid crystal MBBA from a microscope slide, a cover glass and a foil for food wrapping or a tape [33]. They observe the planar cell under a polarizing microscope (a school microscope with $M = 40$ or 100 and two crossed polarizing foils). At this point students should remember the descriptive definition of optically anisotropic materials and find out that liquid crystals are their representatives. Then they rotate the polarizing foils and observe how colours change (see figure 6). This experiment also illustrates a concept of complementary colours [34]. Afterwards students heat the cell and observe colour changes. An experiment where molecules are ordered is done next. Students make micro notches on a microscope slide by rubbing it by a velvet soaked in alcohol. Molecules orient with their long axes parallel to the surface and the rubbing direction. A similar process is used in the fabrication of liquid crystal displays. They observe the cell with the ordered liquid crystal under the polarizing microscope.

Finally, the cell is heated by a hair-dryer and students observe the phase transition that appears as a dark front moving through the sample ending in a dark image when

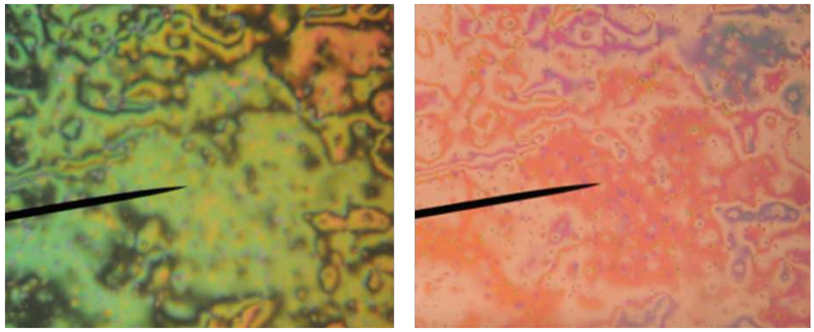


Figure 6. A planar cell with non-ordered molecules of MBBA under a polarizing microscope. The polarizers are perpendicular (left) and parallel (right).

the liquid crystal between crossed polarizers is in the isotropic phase. The lab work is concluded by a discussion of how one pixel in the LCD works, relating the changes of the liquid crystalline structure due to the electric field to the transmission rate of the pixel. At this point the fact that colour filters are responsible for colours of each part of the pixel is also emphasized.

3. Pilot evaluation of the teaching module

The aim of our study was development of a teaching module for non-physics students, which could also be implemented for the high school students. Our goal was to give future primary school teachers basic knowledge about liquid crystals, so that they will be able to answer potential questions of younger students when they will be teachers themselves. Therefore, the teaching module described in the previous section was preliminary tested by a group of 90 first year students enrolled in a four-year University program for Primary school teachers at the Faculty of Education (University of Ljubljana, Slovenia) in the school year 2010/11.

In this section we present the evaluation of the module as regards the efficiency of teaching intervention: which concepts do students assimilate and comprehend and to what extent?

3.1. Methods

3.1.1. Participants First-year pre-service teachers (future primary school teachers) were chosen for testing the teaching module. They were chosen, because their pre-knowledge on liquid crystals is just as negligible as the pre-knowledge of students from other faculties and study programs (see section 4). In addition, the pre-service teachers do not have any special interest in natural sciences, but they have to be as scientifically literate as everyone else who has finished high school. And most important, the pre-service primary school teachers form the only homogeneous group that has Physics included in the study program and is, at least approximately, large enough to allow for a quantitative study. In the group of 90, 6 were male and 84 female students. They

were on average 20.1 years old ($SD = 1.6$ years). On average, they achieved 19.7 points out of 34 ($SD = 3.6$) on the final exam at the end of the secondary school. The average achievement on the final exam in Slovenia was 19.5 points out of 34 and a total of 8842 candidates attended the final exams in spring 2010. The studied group consisted of predominantly rural population with mixed socio-economics status.

3.1.2. Data collection and evaluation The data collection took place by a pre-test, classroom observations of the group work, worksheets and tests. The pre-test had 28 short questions. The first part (7 questions) was related to a general data about a student: gender, age, secondary school, final exam, residence stratum and motivation for science subjects. The second part (19 questions) was related to liquid crystals, their existence, properties and microscopic structure. The pre-test was applied at the beginning of lecture related to liquid crystals. Those students who did not attend the lecture filled in the pre-test before the beginning of the compulsory lab work in chemistry.

The worksheet for the lab work in chemistry includes a procedure to synthesise liquid crystal MBBA, a reaction scheme, observations and conclusions regarding the synthesis and questions from chemistry related to liquid crystals and the lab work.

The worksheet for the lab work in physics presents properties of polarizing foils and optically anisotropic materials and experiments with the liquid crystal MBBA.

Test 1 includes 17 short questions related to the knowledge obtained during the lecture and lab work. Test 1 was held immediately after the end of the physics lab (in May 2011).

Test 2 was a part of an exam held 4 weeks later (June 2011). It has 17 questions that, again, cover the contents of the lecture and lab work. Questions on test 2 were similar to questions given on the pre-test and test 1.

The study provided an extensive set of data but in this paper we will focus only on students' comprehension of new concepts.

3.2. Results and discussion

Results of the pre-test show that 94.4 % of students have already heard of liquid crystals. The percentage is so high, because we were testing students informally obtained knowledge about liquid crystals as a part of another study held at the beginning of the academic year. One student said: "When we got the questionnaire at the beginning of the academic year I was ashamed because I did not know anything about liquid crystals. When I came home I asked my father and checked on the web what they are. These experiments definitely bring them closer to me." Such an interest is a rare exception, however, most of the students remembered the term "liquid crystals", which was a central point of the questionnaire that they filled in at the beginning of the academic year 2010/11.

Since lectures are not compulsory only 37 students attended the lecture. 150 students attended compulsory laboratories. They worked on the synthesis a week after

the lectures and another week later on experiments with liquid crystals at the physics lab. Students worked in groups of 3 or 4 in the chemistry lab and in pairs in the physics lab. However, the whole data (tests and worksheets) was collected only for 90 students, therefore we present only their achievements.

All the groups made the synthesis successfully according to the procedure written in the worksheets. 40 syntheses out of 40 were successfully carried out which was confirmed by measuring the melting and clearing temperature of the synthesized liquid crystal MBBA. On average 63.3 % of worksheets were correctly filled in ($SD = 13.0$ %).

All the experiments described in section 2.4.3 were successfully carried out in the physics lab. The only difference was that students did not prepare the wedge cell by themselves. Due to the lack of time cells were prepared in advance. On average 84 % of worksheets included correct answers to questions and observations ($SD = 9$ %).

On the pre-test students on average achieved 24.0 % of all points. Their achievements show that their prior knowledge about liquid crystals was limited, as expected. On test 1 that was held immediately after the physics lab, students on average achieved 68.1 % (see table 1). Test 2 was a part of a regular exam in Physics. On test 2 students on average achieved only 63.5 % points. The reduced performance on test 2 can be explained by the research on memory and retention, which suggests that many standard educational practices, such as exams and a great emphasis on the final exam, which encourages studying by cramming, are likely to lead to the enhanced short-term performance at the expense of a poor long-term retention [35].

Table 1. Students achievements on tests

Test	Average number of achieved points (max)	*SD*	Percentage of achieved points
Pre-test	6.0 (25)	2.9	24.0
Test 1	14.0 (20.5)	2.4	68.1
Test 2	14.0 (22)	2.6	63.5

Figure 7 shows the distribution of students vs. the achieved points on the pre-test, test 1 and test 2. The percentage of students who achieved higher scores on tests 1 and 2 with respect to the pre-test is evident. The expected level of knowledge about liquid crystals is the highest immediately after the activities. From figure 7 it is seen that most students achieved less than 50 % of points on the pre-test. On test 1 most of the students achieved over 50 %. It is clearly seen that the percentage of students achieving higher percentage of points on test 2 is lower than on test 1, when the impressions of the lab work were still fresh in mind.

A comparison of the percentage of correct answers on selected questions from the pre-test, test 1 and test 2 (table 2) shows further details of students comprehension. Questions on tests were not always exactly the same, but they covered the same contents. The results show that the percentage of students who answered correctly is higher on tests 1 and 2 in comparison to the pre-test, which shows the efficiency of the teaching

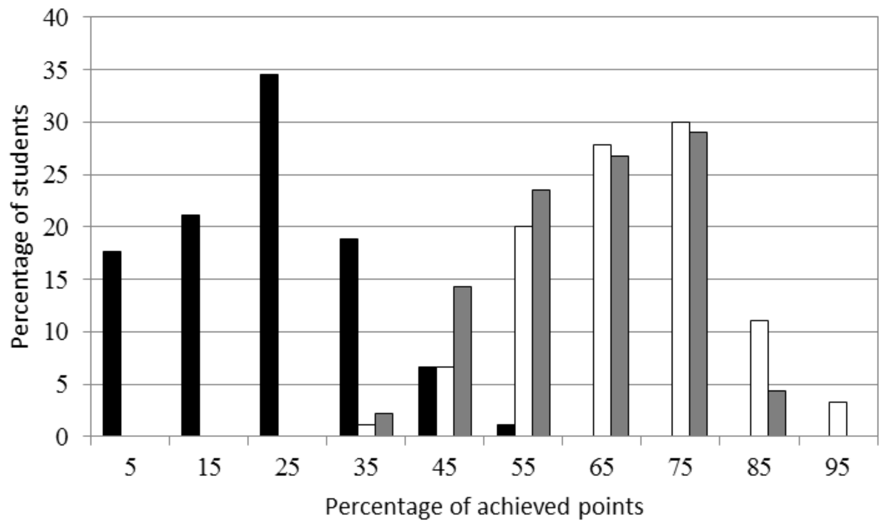


Figure 7. Distribution of the percentage of students vs. percentage of achieved points on tests. Black: pre-test; white: test 1; grey: test 2.

module.

On test 1, 73 % of students correctly answered that liquid crystals are a state of matter. The percentage of students who answer correctly this question on test 2 is smaller. It seems that the deeply rooted misconception about the existence of only three states of matter prevailed after some period of time over new concepts met only during the teaching about liquid crystals.

As much as 93 % of students stated at least one product with liquid crystals on test 2. The percentage of students who underlined correctly all three properties of liquid crystals which are important for their applications, i.e. colours, birefringence and electric properties, is the highest on test 2.

On both tests approximately 60 % of students agreed with the statement that liquid crystals are also in living organisms and 80 % knew that double refraction can be observed in anisotropic materials.

Liquid crystals are liquid in the liquid crystalline state was a statement with which 76 % of students agreed on both tests.

On test 2, 88 % of students knew that an electric field has an effect on the liquid crystal molecules.

The biggest jump in knowledge was detected in the question related to the propagation of light in a birefringent material. On test 1, 98 % of students correctly sketched that the laser beam splits into two beams in birefringent materials. However, the percentage of students who assimilate this was lower, only 58 %. The concept is very difficult and students did not have any preliminary knowledge about it. However, experiments were straightforward in showing that a single light beam splits into two, which is consistent with the phrase “double refraction”.

Finally, 100 % of students sketched the distribution of molecules in the liquid

crystalline state correctly on test 1 while the percentage was reduced to 73 % on test 2. The result is certainly again influenced by the lab work, where the reasons for the anisotropic properties based on the microscopic structure were discussed in detail.

The results of tests 1 and 2 show that fresh impressions from the lab faded away by test 2. This is expected for rather disinterested students that, unfortunately, are rather common in this specific study program. Nevertheless, the results offer an interesting starting point for more extensive research on retention with respect to interest in different physics phenomena.

Table 2. The percentage of correct answers per question on the pre-test and tests

Question	Percentage of student who answered correctly Pre-test	Test 1	Test 2
Liquid crystals are a state of mater.	16	73	61
Write down a product with liquid crystals.	38	86	93
Which properties are most important for the application of liquid crystals? You can choose more than one property.	34	76	87
Substances with liquid crystalline properties appear in living organisms.	18	61	60
Double refraction can be observed in the anisotropic materials.	18	81	82
Liquid crystals are solid in the liquid crystalline state.	43	76	76
Electric field can influence the orientation of the liquid crystal molecules.	49	67	88
Draw the light propagation from air to water and from air to the birefringent material.	2	98	58
Draw the distribution of molecules in liquid crystals.	39	100	73

The evaluation of the teaching module shows that it efficiently increases the knowledge about liquid crystals. By comparing the results of the pre-test, test 1 and test 2 one can conclude that the teaching module was appropriately designed and it allows for the development of concepts related to liquid crystals (table 2). Students were actively involved in the learning process. Their engagement was the lowest during the lecture. At the chemistry lab work students worked in groups of 3 or 4 in a lab with only 2 fume hoods. Due to the waiting for hoods during the synthesis of MBBA not all the members of a group were fully focused on the synthesis. There were also 20 minutes of "free"time due to the time needed for the reaction. So, one should consider the possibilities of better organization of the chemistry lab work in order to keep the students focused on the work. At physics lab students worked in pairs and were more active throughout. It has to be pointed out again that mostly female students were included in the study, the fact that might affect the generality of the conclusions.

However, the study confirms that students in general assimilated the most important concepts related to liquid crystals and their application. The results of the tests confirm that, after the teaching module, students were not only aware of liquid crystals but they also learned their relevant properties.

4. Discussion and conclusions

Liquid crystals are materials that flow like liquids and have physical properties of solid crystals. They are quite common both in nature and technology where they are used in laptops, mobile phones, mp4-players etc. At the same time liquid crystals are an important topic in current scientific research. Liquid crystals are therefore a topic which fulfils two major conditions for being relevant and motivating for students. Because of that we have designed a teaching module which has three parts: the lecture, chemistry lab and physics lab. The aim of the module is to give students a general knowledge about liquid crystals, their properties and the principles of how LCDs work.

The lecture gives the basic knowledge about liquid crystals and their properties. With the lab work students strengthen and expand their knowledge. They synthesize liquid crystal MBBA, they use their own product, i.e. MBBA, in experiments where they observe and discuss an additional phase transition, the properties of optically anisotropic materials in general, double refraction and colours observed in liquid crystalline cells.

The module was tested by 90 first-year, mostly female, students in the study program for teachers for the lower grades of elementary school in the academic year 2010/11. These pre-service teachers have no preference to natural sciences. The knowledge obtained by the teaching module was confirmed by results of the tests. Students on average achieved 68.1 % on the test immediately after the activities and 63.5 % on the test which was a part of an exam a month later. The achievements show a significant increase in the knowledge about liquid crystals, since at the pre-test students achieved on average only 24.0 %.

Can the results of the study for this specific group be generalized to a general population of the first year university students? The group consisted of future primary school teachers and it is not obvious that one can make general assumptions based on the results obtained for this group.

In order to find out if the results obtained by this group can lead to general conclusions we performed additional studies prior to the study reported in this paper. We used a liquid crystal questionnaire (LCQ) to test the informally obtained pre-knowledge about liquid crystals of the first year students at various study programs at the University of Ljubljana [36]. Within the LCQ we assessed other circumstances like the intellectual level of the first year students at different representative study programs in order to estimate the equivalence of the tested and a general group. The results of the study performed on a more general and wider sample of 1121 students shows that a general student pre-knowledge about liquid crystals is practically negligible (table 3), although male students showed statistically significant better achievements on

LCQ than female students. This fact is in agreement with the findings of Haeussler and Hoffmann [37], which argue that male students are more interested in technology and application of science than female students.

Table 3. Comparison between the achievements on LCQ of pre-service primary school teachers from Faculty of Education (pilot study group), students from Faculty of Education and students from University of Ljubljana

		Pilot study group ($n = 82$)		Faculty of Education ($n = 278$)		University of Ljubljana ($n = 1121$)	
Achievements on the LCQ (No. of points out of 8)		1.3	($SD = 1.4$)	1.4	($SD = 1.4$)	1.9	($SD = 1.5$)
Achievements on the final exam (average in Slovenia: 19.5 points out of 34)		19.0	($SD = 3.9$)	19.5	($SD = 4.7$)	22.0	($SD = 5.1$)
Gender and achievements on LCQ	Male	6 %	1.8 ($SD = 1.3$)	10 %	2.4 ($SD = 1.3$)	32 %	2.7 ($SD = 1.5$)
	Female	94 %	1.25 ($SD = 1.4$)	90 %	1.3 ($SD = 1.4$)	68 %	1.5 ($SD = 1.4$)
	t-test	$t = 0.840$	$p = 0.404$	$t = 3.691$	$p = 0.000$	$t = 13.371$	$p = 0.000$

The difference between the pre-service students and students from faculties where the main study field is science and technology is in motivation for natural sciences. The students in the study fields connected to natural sciences and technology definitely have higher interest in natural sciences and therefore it is somehow expected that their achievements on LCQ will be higher. The assumption was confirmed. There are statistically important differences in achievements on LCQ between the students of natural sciences and technology and those who study social sciences and humanistic (see table 4).

Table 4. Achievements on the LCQ regarding the field of study and the natural sciences fields

Field of study ($n = 1121$)	percentage of students	number of achieved points out of 8	SD	t	p
natural sciences or technology	41.7	2.5	1.6	12.712	0.000
social sciences or humanistic	58.3	1.4	1.6		

To conclude, the results from the testing of informally gained knowledge at the end of the secondary school of the pre-service teachers and the students from different faculties on average do not differ: in both samples the lack of knowledge about liquid crystals was detected. Based on the research of prior knowledge it can be said that students that are interested in natural sciences and technology would assimilate at

least as much knowledge about liquid crystals from the teaching module as the pre-service teachers did. Since the results of prior knowledge show statistically significant differences between the knowledge of male and female students one can even dare to conclude that the male students would achieve better results on testing of the module as female students. One can therefore safely conclude that a general audience would achieve at least as good results as the group of students involved in this study. It must be stressed that we have designed the module in which students acquire new knowledge relevant to liquid crystals and their applications, as confirmed by the implementation and the evaluation of the module. Module can also be used as a teaching module at more specialized physics courses. Of course there are still opened issues that we intend to explore. Since we know that the module is appropriate for students that are not motivated in science we will work on the adaptation of module for students motivated in natural sciences. The module presented in this paper can be readily used in the introductory physics courses, and with appropriate modifications it can also be used at lower levels of education.

Evaluation of the model raised several questions that need to be addressed in the future: How do practical experiences influence the knowledge about liquid crystals?, How does a new learning environment influence the knowledge?, How do the chosen teaching methods influence the study process?, etc. However, the whole study and its evaluation show that it is worth an effort to develop new modules on topics related to the current scientific research and everyday technology.

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